Search for New Physics in B Decays¹

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We review recent important progresses at the B factories and discuss the future prospects. We also comment on how we might proceed to search for new physics.

1 Introduction

Much progress in B physics has been achieved over the past few years. Both KEK and SLAC have achieved their corresponding design luminosity goals, and are working hard to surpass them. The $B \to \psi K_S$ asymmetry has been discovered. The direct CP asymmetry has been discovered in the $B \to K\pi$ decay. According to the Belle result, the $B \to \pi\pi$ CP asymmetry shows direct CP violation. First measurements of ϕ_2 and ϕ_3 have been made as well as polarization studies of $B \to \phi K^*$, $\rho \rho$, ρK^* .

In this note, we shall review important B factory results and then discuss possibility for the upgrade.

2 Selected achievements at B factories

2.1 ϕ_1

Who would have thought 5 years ago that we have a precision measurement of CP asymmetry in $B \to \psi K_S$ decay?

The first angle of the unitarity triangle shown in Fig. 1 to be measured was ϕ_1 :

$$\sin 2\phi_1 = +0.728 \pm 0.056 \pm 0.023$$
 Belle[1],
 $\sin 2\phi_1 = +0.722 \pm 0.040 \pm 0.023$ BABAR[2]. (1)

The error is now less than 5%. While this is certainly enough to declare the correctness of the Kobayashi-Maskawa theory, it is not enough, if we want to use this information to look for New Physics beyond the Standard Model. It is worthwhile measuring it to the accuracy of 1% as the theoretical uncertainty in relating this asymmetry to ϕ_1 is of that order.

¹Presented by A. I. Sanda

2.2 ϕ_2

The next challenge is ϕ_2 , but we are not so lucky here. We have both tree and penguin amplitudes contributing to the $B \to \pi\pi$ decay. Nevertheless, it is of great interest to pursue the time dependent CP asymmetry:

$$\frac{\Gamma_{\pi^{+}\pi^{-}}(t) - \overline{\Gamma}_{\pi^{+}\pi^{-}}(t)}{\Gamma_{\pi^{+}\pi^{-}}(t) + \overline{\Gamma}_{\pi^{+}\pi^{-}}(t)} = A_{\pi^{+}\pi^{-}}\cos(\Delta M t) + S_{\pi^{+}\pi^{-}}\sin(\Delta M t), \tag{2}$$

where

$$A_{\pi^{+}\pi^{-}} = \frac{|\overline{\rho}(\pi^{+}\pi^{-})|^{2} - 1}{|\overline{\rho}(\pi^{+}\pi^{-})|^{2} + 1} \qquad S_{\pi^{+}\pi^{-}} = \operatorname{Im}\left(\frac{q}{p}\overline{\rho}(\pi^{+}\pi^{-})\right). \tag{3}$$

We can easily show that

$$|A_{\pi^{+}\pi^{-}}|^{2} + |S_{\pi^{+}\pi^{-}}|^{2} \le 1. \tag{4}$$

Fig. 2 shows both Belle and BABAR results[3]. While it is tempting to say that the direct CP violation in $B \to \pi\pi$ (non-vanishing $A_{\pi^+\pi^-}$) has been discovered at Belle, we feel that we should wait until their data comes within the circle. Note that if it is established that the data point lies outside of the unit circle, it signals violation of quantum mechanics.

Both Belle and BABAR observe the $B \to \pi^0 \pi^0$ decay:

$$Br(B \to \pi^0 \pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$
 BABAR[4],
 $Br(B \to \pi^0 \pi^0) = (2.32 \pm 0.48 \pm 0.22) \times 10^{-6}$ Belle[5]. (5)

This is very encouraging. Isospin analysis can be done. This may be a place where B factories continue to have the edge even after LHC turns on. Certainly, Super B luminosity should be defined to be that luminosity which gives 1% measurement of ϕ_2 using the isospin analysis.

2.3 ϕ_3

The next challenge is ϕ_3 . One of the most promising ways is to make use of the fact that we can not tell whether the intermediate state is D^0K^{\pm} or \overline{D}^0K^{\pm} when we observe $D, \overline{D} \to K_S\pi\pi$

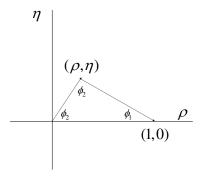


Figure 1: The unitarity triangle.

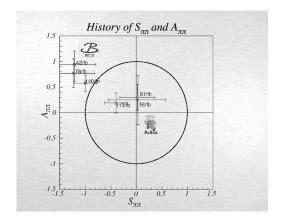


Figure 2: Belle and BABAR results on $B \to \pi\pi$ CP symmetry. The points on the upper left side represent Belle data and the points in the center represent BABAR data.

decay products in the final state:

$$B^{\pm} \rightarrow D^{0}K^{\pm} \rightarrow K_{S}\pi\pi K^{\pm},$$

$$B^{\pm} \rightarrow \overline{D}^{0}K^{\pm} \rightarrow K_{S}\pi\pi K^{\pm}.$$
 (6)

Then amplitudes for these decays interfere, generating CP violation. This method was first suggested in Ref.[6].

First results have been obtained:

$$\phi_3 = (77^{+17}_{-19}(stat) \pm 13(syst) \pm 11(model))^{\circ}$$
Belle[7],
 $\phi_3 = (88 \pm 41(stat) \pm 19(syst) \pm 10(model))^{\circ}$ BABAR[8]. (7)

Future progress in this method seems very promising. We are getting into an era where we are starting to get results on the angles of the unitarity triangle. We should compute the required luminosity for the B factory upgrade based on a 1% determination of ϕ_2 and ϕ_3 .

2.4 Direct CP asymmetries in $K\pi$

Large direct CP asymmetry in $B \to K\pi$ decay has been predicted in the PQCD method and it has been observed in:

$$\frac{\mathrm{BR}(\overline{B} \to K^- \pi^+) - \mathrm{BR}(B \to K^+ \pi^-)}{\mathrm{BR}(\overline{B} \to K^- \pi^+) + \mathrm{BR}(B \to K^+ \pi^-)} = -0.113 \pm 0.019 \tag{8}$$

An asymmetry of similar size has been predicted in $B^{\pm} \to K^{\pm}\pi^0$ but actual measurement shows that:

$$\frac{BR(B^- \to K^- \pi^0) - BR(B^+ \to K^+ \pi^0)}{BR(B^- \to K^- \pi^0) + BR(B^+ \to K^+ \pi^0)} = 0.04 \pm 0.04$$
 (9)

Theoretically, the fact that these asymmetries must be equal follows rather generally if the color suppressed amplitudes and electroweak penguin diagrams are small. Experimental measurement shows that these amplitudes are not negligible, and that they play an important role. If these amplitudes are important they may also modify $B \to \pi^0 \pi^0$ decay rate. Details of this type of analysis has been presented by Yoshikawa.

3 New Physics searches

3.1 $B \rightarrow \phi K_S$

In the Standard Model (SM), the amplitudes for $B \to \psi K_S$ and $B \to \phi K_S$ have equal phases. So, we expect $S_{\phi K_S} = S_{\psi K_S} = \sin(2\phi_1)$. But, Belle obtained[9]:

$$S(\phi K^0) = +0.06 \pm 0.33 \pm 0.09,$$

 $A(\phi K^0) = +0.08 \pm 0.22 \pm 0.09.$ (10)

Note that the Belle result for $S(\phi K^0)$ is dramatically different from the previous result, $S(\phi K^0) = -0.96 \pm 0.5^{+0.09}_{-0.06}[10]$. This is due to the fact that their new measurement with new vertex detector yielded $S(\phi K^0) = +0.78 \pm 0.45$. Averaging all the data, they obtained the value shown in (10). While the data taken with the new vertex detector yields roughly the result $\sim \sin(2\phi_1)$, as expected from the SM, and a Monte Carlo study shows that the probability for this sign flip-flop is about 4.5%, it is nevertheless mind boggling.

The result of Eq. (10) is off from the SM prediction by about 2.2σ . One of the authors AIS) is reminded of what Professor Wong-Young Lee told him once when he was a post doc at Columbia. He said, "A 3σ effect goes away half of the time!" So, we would wait until there is more convincing data before we tell ourselves that New Physics has been discovered. But, depending on the confidence of the experimentalists, this discrepancy should be a major motivation for building the B factory upgrade.

3.2 Dilepton asymmetries in $B\overline{B} \rightarrow l^{\pm}l^{\pm} + anything$

If there is New Physics (NP), it might first show up in ΔM . Obviously, when we search for NP, the SM contribution is the background. Since ΔM is of the second order in the weak interaction, it may be easier to observe NP contributions here. We define[12]:

$$M_{12} = M_{12}^{SM} + M_{12}^{NP} \equiv \frac{\Delta M}{2} \left(R_{SM} e^{2i\phi_1} + R_{NP} e^{2i\theta} \right) = \frac{\Delta M}{2} e^{2i\phi}, \tag{11}$$

where M_{12}^{NP} is the NP contribution to M_{12} . The dilepton CP asymmetry is given by [11]:

$$A_{SL} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \operatorname{Im} \frac{\Gamma_{12}}{M_{12}}$$

$$= r \operatorname{Im} \left(\frac{V_{ub}V_{ud}^* + V_{cb}V_{cd}^*}{V_{tb}V_{td}^* + \frac{R_{NP}}{R_{SM}}|V_{tb}V_{td}^*|e^{2i\theta}} \right)^2 + \mathcal{O}\left(r\frac{m_c^2}{m_b^2}\right), \tag{12}$$

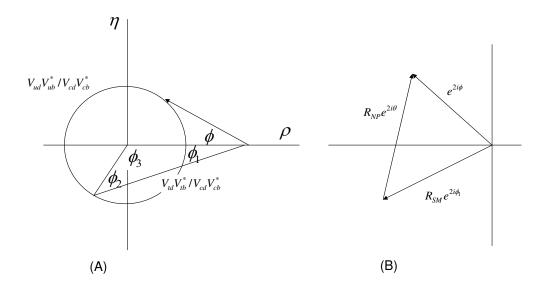


Figure 3: Suppose there is NP which contributes to M_{12} . The experimental measurement of the ψK_S asymmetry gives ϕ as shown in (A). Let us entertain an extreme situation where ϕ_3 is negative. Then the unitarity triangle is located below the horizontal axis as shown here. Figure (B) shows the relationship (see Eq. (9)) between the vector representing the observed asymmetry, $e^{2i\phi}$, the vector representing NP, $R_{NP}e^{2i\theta}$, and the vector representing the SM contribution, $R_{SM}e^{2i\phi_1}$.

where $r = \mathcal{O}(10^{-3})$ is computed in the SM. If R_{NP} is not present, the unitarity constraint of the KM matrix forces the leading term to vanish and the asymmetry is $\mathcal{O}\left(r\frac{m_c^2}{m_b^2}\right)$.

The actual computation of $\frac{\Gamma_{12}}{M_{12}}$ may be tricky as it may receive substantial contribution from long distance effects. Here we assume that contributions from intermediate states with $\alpha\beta$ ($\alpha, \beta = u$ or c) quarks appropriately average the long distance effects, and give a sufficiently good approximation. The fraction $\frac{\Gamma_{12}}{M_{12}}$ has been computed including the next to leading order QCD corrections[14]. Write contribution to $\frac{\Gamma_{12}}{M_{12}}$ from the box diagram where the inner lines are (α, β) quarks as

$$F_{12}^{\alpha\beta}(V_{\alpha b}V_{\alpha d}^*)(V_{\beta b}V_{\beta d}^*). \tag{13}$$

Then the result is given as 2 :

$$\frac{\Gamma_{12}}{M_{12}} = \frac{(V_{tb}V_{td}^*)^2}{M_{12}^{SM}} \left[-F_{12}^{cc} + 2(F_{12}^{uc} - F_{12}^{cc}) \frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*} + (2F_{12}^{uc} - F_{12}^{cc} - F_{12}^{uu}) \frac{(V_{ub}V_{ud}^*)^2}{(V_{tb}V_{td}^*)^2} \right], \quad (14)$$

The dilepton CP asymmetry is written as a function of ϕ_1 as follows:

$$A_{SL} = Im\{\frac{\Gamma_{12}}{M_{12}^{SM}}\}R_{SM}\cos 2(\phi - \phi_1) - Re\{\frac{\Gamma_{12}}{M_{12}^{SM}}\}R_{SM}\sin 2(\phi - \phi_1)$$
 (15)

The KM factors in Γ_{12}/M_{12}^{SM} and R_{SM} can be also written as the functions of ϕ_1 . In the SM, ϕ_1 should be same with ϕ which is measured by the CP asymmetry in $B \to \psi K_s$ so that the

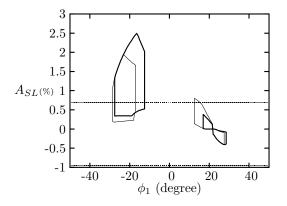
 $^{^2 \}text{The actual expression for } F_{12}^{\alpha\beta} \text{ is given in Ref.} [14]$

contribution is only the first term in Eq. (15) and comes from the imaginary part of the second and third terms in Eq. (14), which vanishes in the limit $m_u = m_c$. The SM contribution is roughly 10^{-4} . The presence of R_{NP} spoils the cancellation and the second term in Eq. (15) becomes non-vanishing. In this case, the CP asymmetry may become as large as a few %.

If this asymmetry is measured to be much larger than $\mathcal{O}(10^{-4})$, it implies the presence of NP. The best limit on this asymmetry is given by Belle[13]:

$$\frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (-0.13 \pm 0.60 \pm 0.56)\%. \tag{16}$$

It is interesting to note that M_{12}^{NP} does not have to be complex. The presence of R_{NP} , which means there may be a difference between ϕ_1 and ϕ , spoils the cancellation of the KM phase, leading to the asymmetry.



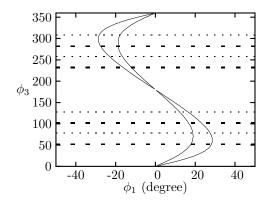


Figure 4: In the left figure the allowed region of the dilepton CP asymmetry A_{SL} for ϕ_1 as the angle of V_{tb} in the SM by taking account of the constraint $\phi_3 = 77^{\circ} \pm 25^{\circ}[7]$ and in the right figure the allowed region for ϕ_3 are plotted. The dotted lines show the bounds from experimental data of ϕ_3 with four fold ambiguity. The regions by thick (thin) line in the left correspond to the bounds shown by thick(thin) dotted lines in the right one. The dotted line in left figure shows the experimental bound of A_{SL} by Belle.

In Fig. 3(A) we show an example of how the $\rho - \eta$ plot gets modified by a non-vanishing R_{NP} . The CP asymmetry in $B \to \psi K_S$ determines ϕ . For an illustration, let us consider a remote possibility that ϕ_3 turned out to be negative. Then we have a situation depicted in this figure. Fig. 3(B) gives the required $R_{NP}e^{i\theta}$.

In Fig. 4, the allowed region for A_{SL} can be shown in terms of ϕ_1 under the constraint of ϕ_3 . But there are four fold ambiguity to measure ϕ_3 and the experimental bounds from $\phi_3 = 77^{\circ} \pm 25^{\circ}[7]$ with the ambiguity are plotted by dotted lines in the right figure. Under taking account of the constraint of ϕ_3 for ϕ_1 , A_{SL} is plotted in the left figure. The region by thick(thin) line in left figure is from the constraints for ϕ_3 by thick(thin) dashed line in right figure. These figures may tell us that combining the constraints from A_{SL} and ϕ_3 can reduce the parameter space for NP and more accurate measurement will help to solve the ambiguity for ϕ_3 . Further improvement of the upper limit is strongly encouraged.

3.3 Lepton number violation

We now know that there is neutrino mixing - lepton flavor number is violated. This may show up in $\tau \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu \tau \to 3e$, $\tau \to e\mu\mu$, etc. Belle has already obtained the following 90% CL limits[15]:

$$Br(\tau \to \mu \gamma) < 3.1 \times 10^{-7},$$

 $Br(\tau \to e \gamma) < 3.8 \times 10^{-7}.$ (17)

It is not so unrealistic to expect that these lepton number violating processes are actually observed in the near future.

It has been customary to study quark physics and lepton physics separately. Since we found that the lepton number is not conserved, it is perhaps advantageous to study the quark system and the lepton system in an unified manner. Searching for lepton number violation in B decays, such as $B \to \tau \mu$ and $B \to 3\mu$, is good example of this unification.

Table 1: Examples of lepton number violating decays. Lepton number violation may very well show up in B decays.

Quark physics	$B \to \tau \mu, \ B \to 3\mu, \ \text{etc.}$
Lepton physics	$\mu \to e\gamma, \ \tau \to 3\mu, \ \text{etc.}$

Conclusion

Much exciting flavor physics with B and τ decays remains uncovered. We hope that Belle and Babar come to an agreement on $A_{\pi\pi}$ and $S_{\pi\pi}$ measurements. This should be followed by first results on the isospin analysis for $B \to \pi\pi$ decays. Theoretical understanding of CP asymmetry for $B^{\pm} \to K^{\pm}\pi^{0}$ decay must be achieved. It is likely that the CP asymmetry for $B \to \phi K_{S}$ will show new physics at the level of less than 5% as opposed to 50-100% level. Dilepton asymmetry will put nontrivial constraints on new physics in the near future. Lepton number violation may be around the corner.

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References

- [1] K. Abe et al. [Belle Collaboration], hep-ex/0408111, submitted to Physical Review D.
- [2] B. Aubert et al. [BABAR Collaboration], hep-ex/0408127 submitted to Phys. Rev. Lett.
- [3] L. Piilonen, talk given at PHENO 2004 workshop in Madison.
- [4] B. Aubert et al. [BABAR Collaboration], hep-ex/0408081.
- [5] K. Abe et al. [Belle Collaboration], hep-ex/0408101.
- [6] I. I. Bigi and A. I. Sanda, Nucl. Phys. B193 (1981) 85-108.
- [7] A. Poluektov et al. [Belle Collaboration], Phys. Rev. D70, 072003 (2004).
- [8] G. Cavoto, BABAR CONF-04/043, talk given at ICHEP2004.
- [9] K. Abe et al. [Belle Collaboration], hep-ex/0409049.
- [10] See HFAG Winter 2004 summary.
- [11] I. I. Bigi and A. I. Sanda, CP Violation, Cambridge University Press, Cambridge, 2000.
- [12] A. I. Sanda, Zhi-Zhong Xing, Phys. Rev. D56 (1997) 6866-6874.
- $[13]\,$ K. Abe et al. [Belle Collaboration], hep-ex/0409012.
- [14] M. Beneke, G. Buchalla, A. Lenz and U. Nierste, Phys. Lett. B576 (2003) 173-183.
- [15] K. Abe et al. [Belle Collaboration], ICHEP04 12-0722.
- [16] SuperKEKB Task Force, KEK Report 2004-4, hep-ex/0406071.